Use of Computer Simulation to Reduce the Energy Consumption in a Tall Office Building in Dubai-UAE

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ABSTRACT

Buildings are a major consumer of energy and thus have a significant impact on the environment. The use of artificial lights is a major contributor to the energy usage in a typical office building using electricity to run the lights and also increasing the cooling load due to its heat dissipation. Proper design for the maximization of natural light helps reduce the use of artificial lights and results in reduction in the buildings energy consumption. Computer simulation of the lighting and energy consumption in a typical tall office building in Dubai-UAE is used to optimize the effectiveness of natural lighting penetration and calculate the associated energy savings. Two alternative building designs are proposed and tested. The overall energy savings for the whole building reached 31.4 % for the proposed oval shaped design. This represents a significant reduction in the buildings electricity load and thus its impact on the environment.

INTRODUCTION

The recent economic growth in the Gulf region particularly in Dubai, United Arab Emirates has led to an increase in the construction of new buildings. This growth attracted many different types of businesses and jobs opportunities in the region. This resulted in a high demand for office buildings in Dubai. This rapid influx of business into Dubai resulted in significant increases in the energy consumption of commercial buildings sector. The high electricity demand is very critical in an area like UAE where the penetration of renewable energy recourses is very limited. Energy efficiency and electricity demand reduction strategies are high priorities in Dubai's efforts to control the escalating levels of energy demand and consumption..

Daylighting is an effective interior design strategy that contributes to occupant comfort (visual and thermal) and occupants' productivity while reducing the energy use in buildings. Energy savings resulting from increased daylighting efficiency is not only the result of reducing lighting electricity consumption but is also due to the reduction in cooling loads and possibilities for smaller heating and air-conditioning (HVAC) equipment size.

In commercial buildings, artificial lighting and cooling represent two of the largest electricity uses. Li and Lam (2001) and Li and Wong (2007) showed that artificial lighting and HVAC systems account for over 70% of the total electricity consumption in commercial buildings. HVAC accounts for over 50% of the total electricity consumption in commercial buildings with lighting coming second at 20–30%. Moreover; heat gain due to artificial lighting represents additional percentage of the total cooling load during the hot summer months. Li, Lam and Wong (2005) reported that the daily energy savings in artificial lighting for open plan office ranged from 1.1 to 1.7 kWh using simple daylight controls. The estimated annual saving was 365 kWh, representing a 33% reduction in the total electric lighting bill. These results highlight the role of daylighting as a key objective for sustainable building design that reduces a building's energy consumption and provides reliable long term benefits for both the building's owners and occupants.

Daylighting Benefits

Psychologically, the presence of controlled daylight has been shown in many studies to significantly improved the overall attitude and well-being of the occupants. Headaches and Seasonal Affective Disorder (SAD) are related to insufficient light levels. Research carried out by Edwards and Torcellini (2002) and Boyce et al. (2003) reported that the use of daylighting decreases the occurrence of headaches, SAD and eyestrain. These ailments are reduced when the daylighting level is improved by using proper spectral light. Other important effects from daylighting include a more positive mood for employees, increased job satisfaction, work involvement, motivation, organizational attachment and lowered absenteeism.

Other studies show that office workers' productivity can increase with the quality of natural light that increases attention and alertness especially during the post-lunch dip and was shown to be helpful in increasing alertness for boring or monotonous work (Heerwagen, 2000). Li and Lam

(2001) studied the effects of windowless offices in Hong Kong. The investigation's results supported the earlier findings (Heerwagen, 2000) that employees in windowless buildings had much less job satisfaction and were substantially less positive. As been reported in California Energy Commission (2003), high illumination levels or glare potential affected office worker performance on three mental function tests, decreasing performance by 15% to 21%.

From an energy efficiency standpoint, Li, Lam and Wong (2005) reported on the potential role that daylight play in reducing electric demands was as high as 33% reduction in energy use of the total electric lighting bill were recorded by applying simple shading protections. The Collaborative for High Performance Schools (CHPS) (2006) pointed out that daylighting can offer great energy savings due to reduced electric lighting loads and in turn, reduced cooling loads. Turning off lights makes a big dent in a company's utility bill. The savings are compounded because when electric lights are off, they're not generating waste heat that has to be removed by a building's air conditioning system. That saves an additional three to five percent in total energy consumption. Properly designed daylighting can reduce energy consumption for lighting by 50 to 80 percent, according to the U.S Green Building Council (USGBC).

The United Arab Emirates lies between latitudes 22°–26.5°N and longitudes 51°–56.5°E, described as the earth's sun belt. The yearly solar radiation for the UAE is believed to be around 2,200 kilowatt hours per square meter, and the direct illumination falling to the earth exceeds 90000 lux in summer, the second highest in the world (Al-Sallal and Ahmed, 2007). Being on the tropic of cancer (24 deg N) results in that the UAE region receiving the highest annual rate of solar radiation and sun illumination. In such a harsh climate of the UAE, which is characterized by high levels of solar radiation and intense sunlight, the design should minimizes direct sunlight by means of shading and providing diffuse daylight reflected from the ceiling.

Bhavani and Khan (2006) pointed that most buildings in the UAE are not designed to achieve proper daylight levels. In office buildings, many offices have deep spaces that are lit from one side only. Many other offices have fully glazed facades facing east and west which creates serious problems of high brightness contrast and acute glare that results in reducing visual comfort and in some cases causing health problems such as headache and fatigue. Aboulnaga (2005) investigated the use and misuse of glass as a building element in offices. He highlighted the large glazed areas in Dubai's offices facades which do not have any protection against overheating and sun's glare in summer. He also introduced some simulations for 15 existing buildings in Dubai to evaluate the current problem of misused glass. His conclusions reinforced the existence of the problem of daylighting but did not provide any detailed solutions except for some suggestions that architects must consider in the design process to achieve good daylight distribution. Systems that can help to redistribute and filter daylight coming from windows and skylights have been recommended by (Al-Sallal 2006 and Al-Sallal and Ahmed 2007) to overcome the high brightness and glare problems in educational spaces in the UAE.

In general Dubai designers suffer from the lack of the necessary design methods and easy-to-use tools for environmental evaluation at an early stage of a design. Therefore, there are few published works directly linked to the specific topic of this research.

Motivation

All of the above motivated the authors to undertake this research. The idea was to use advanced daylighting simulation to evaluate the effectiveness of current office buildings design trends in Dubai and to propose and test revised designs which could provide better daylighting. The effects of improved daylighting on the cooling load will also be considered when estimating the changes in the total electricity consumption of the buildings with the original and revised designs.

METHODOLOGY

For many years, daylighting design was mainly based on rules-of-thumb and the architect's experience. Simple methods were introduced in the early developments for daylighting testing methods which mainly focused on the quantity of daylight as engineered solution. The increased importance of daylighting and the high expenses of energy led investigators to introduce mathematical methods as an attempt to enhance daylighting performance. Today modern performance methods are just as varied as the different technologies that take place in daylight design. Methods of testing daylight included many types of mathematical formulas, laboratory modeling and simulation software.

Aburdene (2001) defined the term Simulation in general as the process of developing a simplified model of a complex system and using the model to analyze and predict the behavior of the original system in reality. Reinhart (2006) defined daylight simulation specifically as a computer-based calculation, which aims to predict the amount of daylight available in a building either under selected sky conditions (static simulation) or during the course of the whole year (dynamic simulation). Computer simulations give very wide options for changing parameters and study daylight in different locations. Simulations calculate quantity values like illuminance and luminance. Results can be presented by different outputs as real image, false color mapping or presenting values in numeric numbers. The technology boom and the recent awareness about the importance of sustainability as design method have opened the door for many different companies to be in competition to develop sustainable simulation engines. The three major relevant simulation packages are: 3D Max Design, Radiance and Daysim.

Reinhart and Fitz (2009) investigated the performance of the above three programs (3D Max Design, Radiance and Daysim) through running of daylighting simulations for a room and comparing the results to the data collected from the actual room being simulated in order to review the capabilities and performance of each software. The results indicated that 3D Max Design is the best tool for daylighting simulations design decisions. Thus this is the software selected for use in this study.

<u>Daylight Performance Metric</u>

Daylight factor (DF) is the most common parameter used to characterize the daylight situation at a point in a building. DF as the ratio of the indoor illuminance at a point of interest to the outdoor horizontal illuminance under a standard uniform sky developed by the overcast Commission International de l'Eclairage (CIE) (Reinhart, 2006). Daylight factor enjoys considerable popularity since it is a quantity which can be measured and/or calculated either based on calculation tables or more refined simulation methods. The calculation of daylight factor depend on the split flux method which states that natural light reaches a point inside a building via three components:

1) Sky Component (SC) directly from the sky, through an opening such as a window.
2) Externally Reflected Component (ERC) light reflected off the ground, trees or other buildings.
3) Internally Reflected Component (IRC) which is the inter-reflection of (SC) and (ERC) off other surfaces within the room.

The major weakness of the daylight factor is that the orientation of the investigated building does not influence the daylight factor since the CIE reference sky is rotationally constant and independent of the geographical latitude of the investigated building. Another shortcoming of the daylight factor approach is that the underlying CIE overcast sky tends to underestimate luminance near the horizon. As a consequence, illuminances in sidelit/toplit spaces tend to be under/over predicted. However, daylight factor is commonly used and provides an indication of how “bright“ or “dark“ the interior of a given building. Since it is based on a single sky condition, its credibility to judge the overall daylight situation in a given building in a given location and orientation is intrinsically limited.

The current study is based in Dubai, U.A.E which has an average cloud coverage not exceeding 9%. Thus daylight factor simulation analysis for a building in Dubai cannot be based on an overcast sky condition built in the DF method and would result in grossly inaccurate data. Aboulnaga (2005) conducted a quantitative analysis in Dubai's towers to assess the impact of glass on the building users' performance in terms of daylight environment. His investigation was to assess whether selected glass provides the recommended daylight factor (DF) and daylight level (DL). He conducted several simulations using Ecotect to evaluate the misuse of glass at different offices in Dubai. His results came to reinforce the existence of very high level of (DF) and (DL) in some of Dubai offices. He used the CIE overcast sky for his simulations, the only sky model available in Ecotect, his program of choice. As noted above, because the overcast sky model neglects the unique characteristics of a locations atmosphere and building orientation, his findings were very inaccurate.

Useful Daylight Illuminances (UDI) was proposed by Nabil and Mardaljevic (2006). It's a dynamic daylight performance metric also based on work-plane Illuminances. UDI aims to determine when daylight levels are ‘useful’ for the occupant, The UDI scheme is used to determine the occurrence of daylight illuminances that:

1. Are within the range defined as useful (i.e. 200–2000 lux).
2. Fall short of the useful range (i.e. less than 200 lux).
3. Exceed the useful range (i.e. greater than 2000 lux).

The suggested range is based on the occupants' visual and thermal comfort and needs. If the daylight illuminance is too small (i.e. below a minimum), it may not contribute in any useful manner to either the perception of the visual environment or in the carrying out of visual tasks. Conversely, if the daylight illuminance is too great (i.e. above a maximum), it may generate visual or thermal discomfort, or both. Illuminances that fall within the bounds of minimum and maximum were called useful daylight illuminances. However the values set by Nabil and Mardaljevic (2006) for Low, Useful and High daylight illuminance may be varied by different investigators in different regions, depening on their interpretation of the term (Useful). Ko et al. (2008) suggested that the range of 200-1000 lux is a more suitable range for useful daylight illuminance in most types of internal spaces. Li and Wong (2007) also considered 1000 lux as the upper illuminance level. From his standpoint, 2000 lux could still be considered an acceptable value from a visual comfort point of view but this value would lead to high heat gain, which is not acceptable for Hong Kong subtropical climate.

The UDI scheme is both informative and simple. It is more complex than the daylight autonomy method, but it gives a much greater insight into the sequential dynamics of daylight illumination. In particular, it gives an indication of the predilection for high levels of illumination that are linked with discomfort glare and heat gains. "UDI is based primarily on human factor considerations, high values of achieved UDI might well be associated with low energy usage for electric lighting, and possibly also for cooling but high values of daylight Autonomy does not indicate for thermal and visual problems" Nabil and Mardaljevic (2006). In addition, UDI metrics provides a more informative and comprehensive assessment of daylight conditions than that which can be gained from daylight autonomy. Thus this is the method that was used in this study.

RESULTS AND DISCUSSION

In this sets of tests, study is focusing on how Useful Daylight Illuminances (UDI) affected by various offices levels within existence of near vertical obstruction. The range of useful UDI range is set to 200-2000 Lux. A reference building plan layout in Shikh Zayed Road (SZR) with a square 30X30 meter plan and a setback of 10 meters from neighboring buildings is used in this study, Fig. 1. The UDI for offices in different levels (low, middle and high; Fig. 2) will be measured and evaluated as well as the related lighting and cooling loads/total load. The UDI for two proposed alternative plan layouts that providing the same built-up area but increase the side setbacks, Fig. 3. Increasing the side setback will allow more natural light especially to the lower floors which in turn is expected to reduce the lighting and cooling loads. The reductions will be compared to the reference values of the original square plan design.

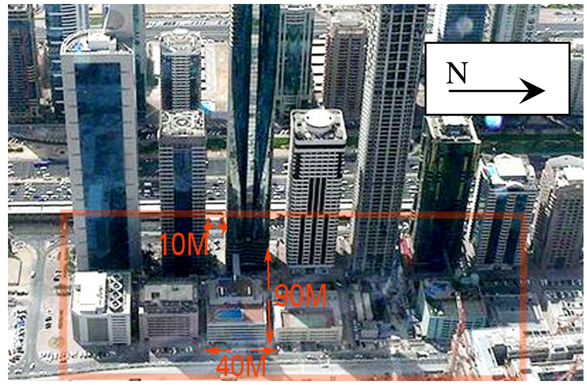

Figure 1. Rectangular plots of SZR (40mx90m) showing the 30X30m tower with only 10 meter separation from adjacent towers. The backside is used as parking lots or facilities areas .

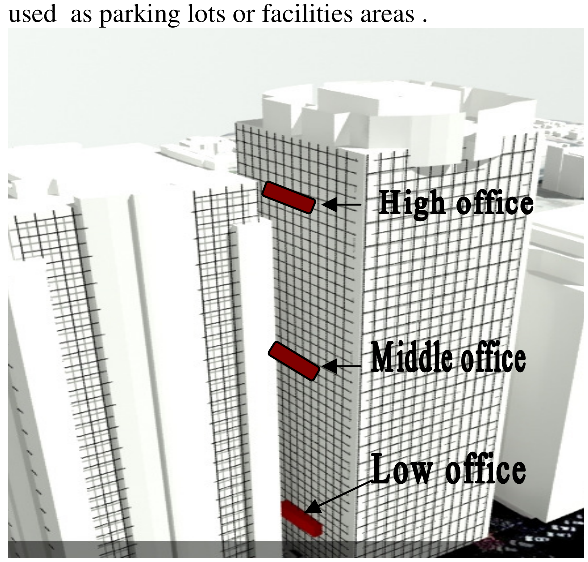

Figure 2. Level of the three offices to be studied.

Table 1 shows a summary of the UDI for the three configurations at the selected levels. It can been seen that the oval configuration offers the highest increase in UDI compared to the original square plan, up 433.3% at the low level. Even the rectangular plan offers marked improvements in UDI over the original square plan. As expected the improvements in the UDI were most significant at the low and middle levels. At the high level the improvement was less yet still respectable at 31.2% and 34.4% for the rectangular and oval shaped buildings, respectively.

The enhanced UDI resulted in significant reductions in the energy used for lighting. Figure 4 shows the lighting energy consumption and percentage reduction compared to the reference square plan for the three configurations at the three floor levels indicated in Fig. 2. The cooling load was also significantly reduced in both new designs, mainly due to the reduction in the heat gain from the artificial lights needed to supplement the natural light entering the floor plan. The cooling load was also reduced due to reduction of the building's East and West facing sides and increased North and South sides, see Fig. 1 for North direction. The changes in the cooling load did not match the changes in the lighting load mainly due to the differences in the shape, length and plan-depth of the buildings.

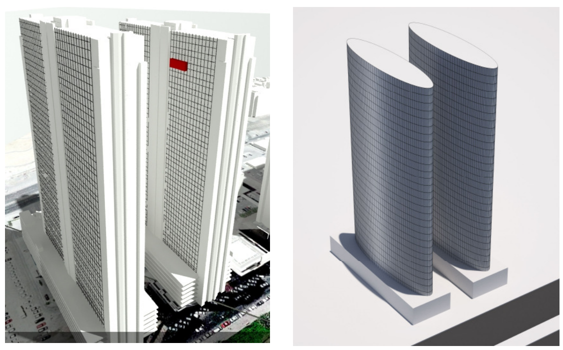

Figure 3. Alternative proposed plans tested, rectangular (left) and oval (right).

Table 1. Summary of the UDI values for the three levels in the three building configurations tested.

Floor level	Building configuration	Average UDI	% Increase in average UDI
Low	Square	12	NA, reference
	Rectangular	52	333.3%
	Oval	64	433.3%
Middle	Square	26	NA, reference
	Rectangular	61	134.6%
	Oval	70	169.2%
High	Square	64	NA, reference
	Rectangular	84	31.2%
	Oval	86	34.4%

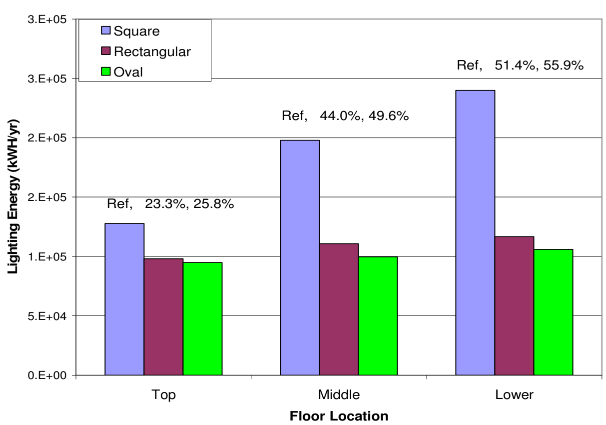

Figure 4. Lighting energy consumption for the three levels in the three building configurations. Numbers *above bars indicate the percentage reduction.*

Table 2 shows a summary of the lighting, cooling and overall load consumptions of the three buildings. Figure 5 shows the cooling energy consumption and percentage reduction compared to the reference square plan for the three configurations at the three floor levels indicated in Fig. 2. Figure 5 clearly shows the high potential for energy saving of the two proposed re-designs. The oval plan is slightly more efficient than the rectangular plan, mainly due to its superior UDI characteristics at the lower levels. Still the rectangular plan is not far off and could be the design of choice when other factors are taken into account such as construction cost and usability of internal spaces.

Table 2. Summary of the different loads for the three levels in the three building configurations tested.

Load type	Floor level	Building configuration	Load value (kWhr/yr)
Lighting	Low	Square	239809
		Rectangular	116590
		Oval	105878
	Middle	Square	197823
		Rectangular	110712
		Oval	99623
	High	Square	127832
		Rectangular	98082
		Oval	94916
	Whole Building	Square	4907541
		Rectangular	2702683
		Oval	2451364
Cooling	Low	Square	160351
		Rectangular	137258
		Oval	146372
	Middle	Square	181863
		Rectangular	152764
		Oval	161674
	High	Square	220542
		Rectangular	189462
		Oval	191760
	Whole Building	Square	4208795
		Rectangular	3708678
		Oval	3801423
Overall	Low	Square	400160
		Rectangular	253848
		Oval	252250
	Middle	Square	379686
		Rectangular	263476
		Oval	261297
	High	Square	348374
		Rectangular	287544
		Oval	286676
	Whole Building	Square	9116336
		Rectangular	6411361
		Oval	6252787

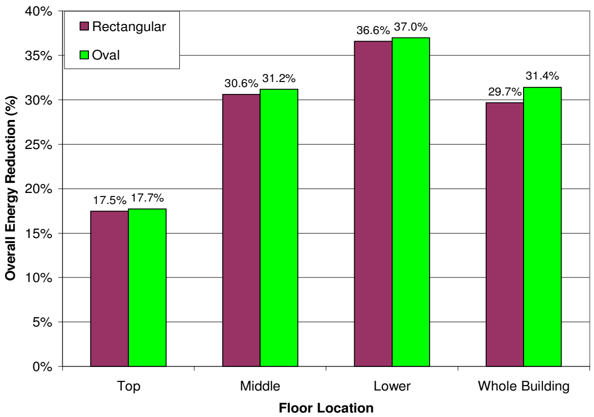

Figure 5. Reduction in overall energy for the three building configurations tested.

CONCLUSIONS

The use of natural lighting in office buildings can significantly reduce lighting and cooling loads. Closely spaced office buildings do not allow for sufficient natural light penetration, especially at the lower levels. Computer simulation along with UDI values were used to test two proposed re-designs of a typical office building in Dubai-UAE. The simulations showed the great potential for energy savings due to the enhanced UDI characteristics of the proposed designs. The oval shaped building achieved an overall energy savings of 31.4% while the rectangular shaped building achieved an overall energy savings of 29.7% compared to the original design. These results clearly show the importance of enhancing natural lighting in office buildings at the design phase in order to reduce the energy requirements of the building.

REFERENCES

Aburdene, M.F. 2001. Computer Simulation of Dynamic Systems. *Building and Environment* 25: 1120-1138.

Al-Sallal, K. A. 2006. Easing high brightness and contrast glare problems in universal space design studios in the UAE: Real models testing. *Renewable Energy* 31: 617–630.

Al-Sallal, K. A. and Ahmed, L. 2007. Improving natural light in classroom spaces with local trees: simulation analysis under the desert conditions of the UAE. *Proceeding of Building Simulation BS-2007 conference, Beijing, China September 3-6.*

Aboulnaga, M. M. 2005. Towards green buildings: Glass as a building element-the use and misuse in the gulf region. *Renewable Energy* 31:631–653.

Boyce, P., Hunter, G. and Howlett, O. 2003. The benefits of daylight through windows . *Lighting Research Center, Troy, New York, USA.*

Bhavani, R. G. and Khan, M. A. 2006. Present Trends and Future Direction of Lighting Control in Dubai. *Middle East Economic Survey.* 50:23-24.

California Energy Commission (CEC). 2003. Windows and Offices: A Study of Office Worker Performance and the Indoor Environment, USA.

CHPS Daylighting Committee Daylighting Forum. 2006. Daylighting Metric Development Using Daylight Autonomy Calculations In the Sensor Placement Optimization Tool., Colorado, USA.

Edwards, L. and Torcellini, P. 2002. Literature Review of the Effects of Natural Light on Building Occupants. *National Renewable Energy Laboratory NREL/TP-550-30769.*

Heerwagen, J. H. and Associates, Inc. 2000. Green Buildings, Organizational Success, and Occupant Productivity. *Building Research and Information* 28: 353-367.

Ko, D. H., Elnimeiri, M. and Clark, R. J. 2008. Assessment and prediction of daylight performance in high-rise office buildings. *The structural design of tall and special buildings* 17: 953–976.

Li, H. W. and Lam, C. 2001. Evaluation of lighting performance in offices buildings with daylight controls . *Energy and Building* 33: 793-803.

Li, H. W., Lam, N. T. and Wong, S. L. 2005. Lighting and energy performance for an office using high frequency dimming controls. *Energy Conversion and Management* 47: 133–1145.

Li, H. W. and Wong, S.L. 2007. Daylighting and energy implications due to shading effects from nearby buildings. *Applied Energy* 84:1199–1209.

Nabil, A. and Mardaljevic, J. 2006. Useful daylight illuminances: A replacement for daylight factors. *Energy and Buildings* 38:905–913.

Reinhart, C.F. 2006. Tutorial on the Use of Daysim Simulations for Sustainable Design. *Institute for Research in Construction. Ottawa, Canada* .

Reinhart, C.F. and Fitz, A. 2009. Experimental Validation of Autodesk 3ds Max Design 2009 and Daysim 3.0. *NRC Project # B3241*.